

Two-dimensional distribution of volatiles in the lunar regolith from space weathering simulations

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[1] We present simulations of space weathering effects on ice deposits in regions of permanent shadow on the Moon. These Monte Carlo simulations follow the effects of space weathering processes on the distribution of the volatiles over time. The model output constrains the coherence of volatile deposits with depth, lateral separation, and time. The results suggest that ice sheets become broken and buried with time. As impacts begin to puncture an initially coherent surficial ice sheet, small areas with a deficit of ice compared to surrounding areas are formed first. As time progresses, holes become prevalent and the anomalous regions are local enhancements of ice concentration in a volume. The 3-D distribution is also heterogeneous because the ice is buried to varying depths in different locations. Analysis of the coherence of ice on 10 cm scales predicts that putative ice sheets in anomalous radar craters are <100 Myr old. Surface frost becomes homogenized within 20 Myr. The simulations show the data from the LCROSS impact and surrounding region are consistent with the ice deposit in Cabeus being >1000 Myr old. For future in situ analysis of cold trap volatiles, a horizontal range of 10 m is sufficient to acquire surface-based measurements of heterogeneously distributed ice. These results also support previous analyses that Mercury's cold traps are young. **Citation:** Hurley, D. M., D. J. Lawrence, D. B. J. Bussey, R. R. Vondrak, R. C. Elphic, and G. R. Gladstone (2012), Two-dimensional distribution of volatiles in the lunar regolith from space weathering simulations, *Geophys. Res. Lett.*, 39, L09203, doi:10.1029/2012GL051105.

1. Introduction

[2] A question of both scientific and exploration interest is how water ice and other volatiles are distributed in permanently shaded regions (PSR) near the lunar poles. Practically, knowledge of volatile contents and their distribution in PSRs will aid in mission planning and design for future human and robotic lunar missions because those volatiles represent a significant potential resource. Scientifically, the PSRs potentially hold volatiles deposited over the

last 2 billion years [Arnold, 1979; Siegler *et al.*, 2011]. This is an unparalleled, accessible record of volatile flux in the inner solar system.

[3] Analysis of the possibility of water and other volatiles existing in PSRs has a long history [e.g., Urey, 1952; Watson *et al.*, 1961; Arnold, 1979]. Yet, the first spectroscopic confirmation of their presence inside PSRs came with the impact of the Lunar Crater Observation and Sensing Satellite (LCROSS) into Cabeus crater near the lunar south pole [Colaprete *et al.*, 2010; Gladstone *et al.*, 2010; Killen *et al.*, 2010]. Lunar data from the 1990s and 2000s provided evidence consistent with the presence of ice in the lunar polar regions; yet it was inconclusive. Neutron spectroscopy from Lunar Prospector returned data consistent with the presence of water ice in the near-subsurface of the Moon in permanently shadowed regions by measuring heterogeneously distributed hydrogen concentrations at both lunar poles [e.g., Feldman *et al.*, 1998; Eke *et al.*, 2009]. Clementine and ground-based radar returned tantalizing, but inconclusive evidence of ice in lunar PSRs [Nozette *et al.*, 1996; Campbell *et al.*, 2006]. Later, Mini-SAR and Mini-RF instruments on Chandrayaan-1 and the Lunar Reconnaissance Orbiter (LRO) detected a radar signature consistent with water ice in some polar craters on the Moon, but not all PSRs [Spudis *et al.*, 2010; Neish *et al.*, 2011]. Similarly, Lunar Exploration Neutron Detector (LEND) on LRO also detected a heterogeneous distribution of hydrogen among lunar PSRs [Mitrofanov *et al.*, 2010]. In addition, Lyman Alpha Mapping Project (LAMP) on LRO detected far ultraviolet (FUV) spectra consistent with frost on the surface of some permanently shadowed regions [Gladstone *et al.*, 2012].

[4] Various measurements that are directly and/or indirectly sensitive to ice in PSRs inherently have different sensitivities, fields of view, and resolution. Data from different instruments often appear to be in conflict about the distribution of volatiles they imply. For example, the weakest spectral feature from LAMP was associated with Shoemaker crater [Gladstone *et al.*, 2012], which had the strongest hydrogen feature from LEND [Sanin *et al.*, 2012]. The impact of LCROSS into Cabeus released water and other volatiles [Colaprete *et al.*, 2010; Gladstone *et al.*, 2010; Killen *et al.*, 2010; Schultz *et al.*, 2010], but abundances were higher than the background amounts detected by neutron spectroscopy, implying heterogeneity within that PSR either in area or in depth [Mitrofanov *et al.*, 2010; Elphic *et al.*, 2011].

[5] To add another level of complication, volatiles emplaced in lunar polar regions are modified over time by space weathering processes including impact gardening [e.g., Arnold, 1979]. Temperatures below 90 K are too low for thermal diffusion and sublimation [e.g., Vasavada *et al.*, 1999; Andreas, 2007; Schorghofer and Taylor, 2007; Paige *et al.*,

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2010; Siegler *et al.*, 2011]; however, volatiles deposited in lunar cold traps are subjected to other destructive mechanisms [Arnold, 1979]. It is important to understand the modification processes on several different scales in order to interpret disparate data in a consistent manner. We present a simulation and sample the results to provide a self-consistent, multi-dimensional view of lunar polar volatiles. This work suggests that the lateral coherence, a property necessary for radar detection of ice, disappears quickly. The oldest ice deposits, invisible to radar, still can produce a signature observable by neutron spectroscopy. Spectroscopy in the ultraviolet can provide crucial input for determining any recent or steady state delivery of volatiles.

2. Model

[6] An ice layer in a cold trap, even if is initially homogeneous, is disrupted by impact gardening. Impacts can act to remove volatiles as well as preserve volatiles. As impacts emplace an ejecta blanket, the layer protects volatiles that had been exposed to the surface from losses to sputtering and sublimation. However, impacts vaporize material, thereby releasing volatiles at the point of impact. As each location on the Moon has undergone a unique impact history, this process introduces heterogeneity into the system.

[7] We incorporate techniques developed to analyze Apollo drill cores [Arnold, 1975; Borg *et al.*, 1976] to create a Monte Carlo model that examines the evolution of ice in a permanently shaded region on the Moon [Crider and Vondrak, 2003a, 2003b] and Mercury [Crider and Killen, 2005]. Previously, the model simulated the evolution over time of ice with depth in a single vertical column of regolith. We have expanded the model to investigate lateral scale lengths of properties of ice. Instead of simulating a single column, we now simulate two columns with adjustable lateral separation. We consider impacts and gardening in the area including the pair of columns and allow any impact to affect whichever simulation columns are in the crater radius or ejecta blanket. Correlations between columns provide a look at how features persist in both time and distance.

[8] The model starts with an initial configuration of water ice. Here, we use a coherent layer of ice on the surface of a given thickness and concentration. The Monte Carlo simulation implements impacts by randomly generating a set of discrete impacts using the frequency and size distribution of impacts of $m > 1 \mu\text{g}$ [Neukum *et al.*, 2001]. When a discrete impactor hits, its location relative to each column of regolith is computed. The model adds or removes material appropriate for the associated crater. The excavation/ejecta layer is handled consistently between the columns. If material is removed from one column and emplaced on the other, the concentration of volatiles in the excavated material factors into the concentration of volatiles in the ejecta layer assuming a variable volatile loss from the impact. The simulations provide a simple approximation of impact cratering that neglects some important aspects of cratering, including compaction and slumping. Smaller impactors are treated as an average accumulation between larger, discrete impacts [Gault *et al.*, 1972] because computation time for handling these discretely increases while the effects of the impacts become smaller. Volatiles at the surface can be lost during exposure to photolysis or sputtering. Thermal diffusion is neglected because the rate is small for $T < 90 \text{ K}$ [Schorghofer and

Taylor, 2007]. That limits this application to the coldest areas on the Moon.

[9] Each model run presented in this paper starts with an initial ice layer on the surface that is 10 cm thick and comprised of 100 wt.% water ice. This is more concentrated than expected, but the results scale with the assumed initial weight fraction of ice. A set of 1000 pairs of columns was run for each lateral separation (1 cm, 10 cm, 1 m, 10 m, 100 m, 1 km). The water concentration as a function of depth for each pair is recorded at times 1, 2, 5, 10, 20, 50, 100, 200, 600, and 1,000 Myr after the ice layer is emplaced.

3. Results

[10] Each Monte Carlo run represents a possible scenario given the inputs to the program. Running 1000 cases with the same program inputs but a different seed to the random generator produces a set of profiles that are representative of what can be expected to occur on the Moon. In general, impacts act to cover the ice layer because the area of the ejecta blanket is larger than the area of the crater. Thus each location on the Moon statistically receives more burial events than excavation events. In any individual run, the ice layer tends to stay intact; buried under a thickness of ejecta. The thickness of the ejecta layer varies from case to case; but the burial rate is 1 mm/Myr on average.

[11] On average, excavation events are deeper than the burial events. Furthermore, excavation events potentially disrupt the ice layer. Excavation removes a fraction of the ice deposit. The resulting ice layer is thinner than the original. The ice concentration in underlying regolith is nearly the same as the original concentration because of the way the code implements an impact. An impact that is large enough to penetrate the ice layer will also affect the adjacent column of material on the lateral scale determined by the depth to diameter ratio of impact craters. As impacts begin to puncture the ice layer, there will be well-correlated areas of decreased ice concentration compared to the surroundings. Both the number of these holes and the size of these holes increase with time as more and larger impacts become likely. As time progresses, buried ice and holes become prevalent and the few undisturbed sections of ice are rare. Thus at later times, the anomalous regions should be expected to have higher ice content than their surroundings.

[12] Figure 1 shows the heterogeneity as a function of depth and column separation. The difference between the ice content in each depth bin for column 1 from that in the same depth bin for column 2 is calculated. The standard deviation, defined here as the sum of the squared differences for each of the 1000 runs divided by the number of runs, is shown for each depth bin at ages (from left to right) 1 Myr, 10 Myr, 100 Myr, and 1000 Myr as a function of lateral separation. Low standard deviation means that the ice layer is still uniform (e.g., the dark area at the top in the left plot) or that there is a homogeneous layer that lacks ice (e.g., the dark area at the bottom of the left plot). The high deviations at the top and bottom of the enriched ice layer show the depths at which some columns have ice and others do not. The surface becomes homogeneous with low water concentration ($f_{\text{ice}} < 1 \text{ wt.}\%$) at $t \sim 20 \text{ Myr}$. Deviations in the ice layer increase with lateral separation in the 100 Myr case and at later times. Samples separated by $> 1 \text{ m}$ would have very different vertical profiles for deposits aged $> 100 \text{ Myr}$.

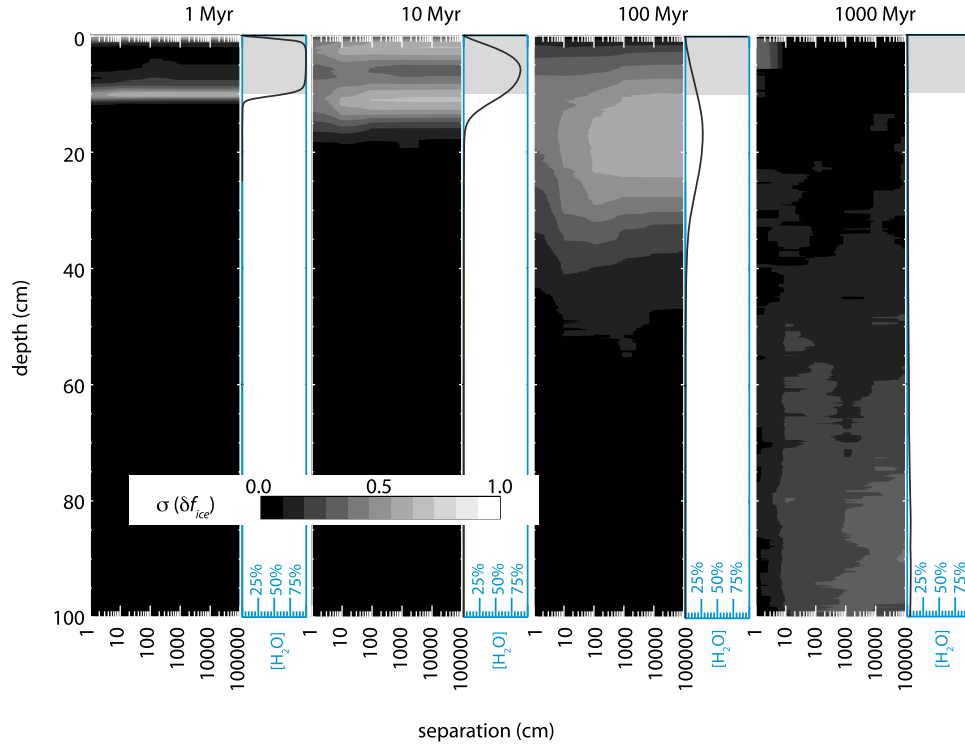


Figure 1. The standard deviation of the value of the concentration of ice as a function of depth in one column compared to another column separated by the amount on the x-axis for an ice layer that was 10 cm thick to start after (from left to right) 1 Myr, 10 Myr, 100 Myr, and 1000 Myr. For reference, the average concentration for the age is provided to the right of each plot.

[13] The next analysis studies the occurrence of dry regions. In Figure 2, for each of the 1000 runs of 100 Myr and 1 m lateral separation, a data point appears showing the average ice content in the top meter of Column 1 vs. Column 2. Four populations appear. The upper right group includes runs in

which both columns retained a significant amount of ice. The population in the upper left is where column 2 retained ice, but column 1 lost the ice after an impact. The converse holds for the constituents in the lower right. The lower left contains the trials where the ice is removed from both columns. The individual profiles of ice content as a function of depth are widely varied in the set of runs, reflecting varying burial depths and thicknesses of retained ice. However, the concentration of the ice, where it is retained, does

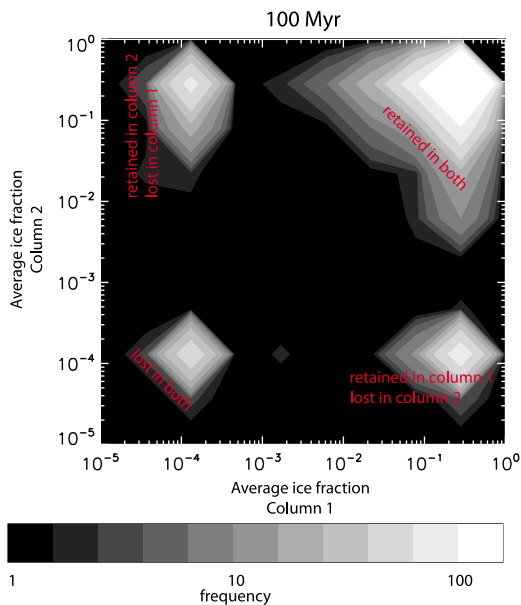


Figure 2. The integrated ice content in one column versus the other column from a set of 1000 runs of 100 Myr and 1 m separation.

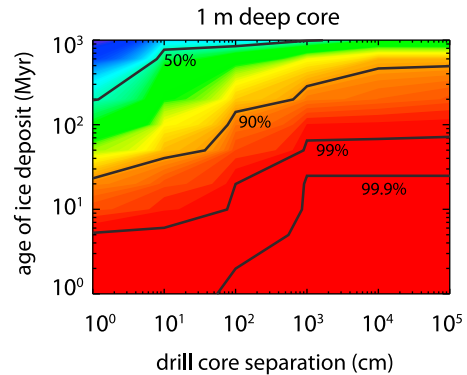


Figure 3. The probability that at least one drill of two drill cores has a measurable amount of water as a function of the age of the deposit and the lateral separation of the two cores. For deposits that are younger than 100 Myr, the probability improves with displacement up to a distance of 10 m. Greater distances do not significantly increase the probability of finding the ice.

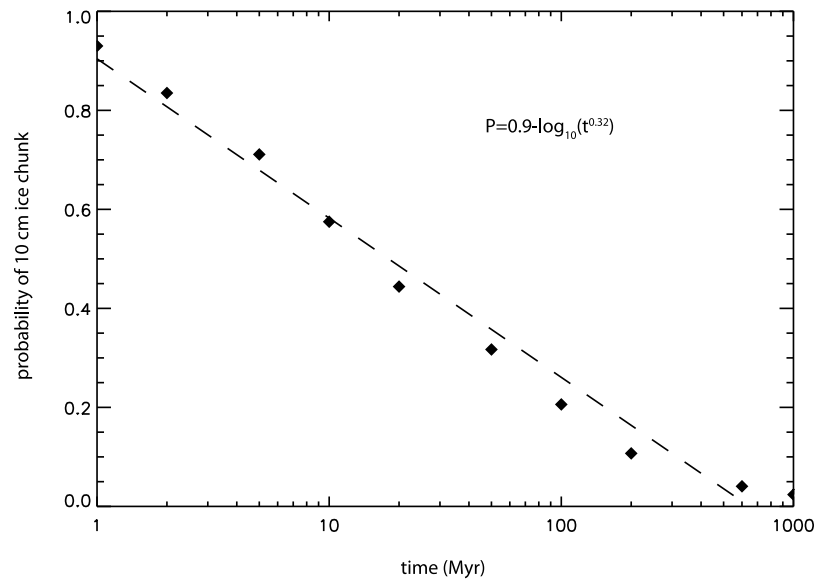


Figure 4. Integrating the ice abundance over original depth from the model runs then counting the occurrence rate that the ice abundance is large and is similar to the ice abundance in the adjacent column provides the probability that an ice block is retained. For the ice in the top 20 cm, the occurrence rate of 10 cm wide ice blocks decreases with time.

not change much from column to column or from the original value.

[14] The number of points in the upper left, upper right, and lower right comprises the number of runs in which at least one of the two columns is “wet,” which we define here as having an average of 1 wt. % ice over a given depth. Dividing the number of points in the shaded area by the total number of runs gives the probability of finding at least one wet spot through sampling two columns at that lateral separation.

[15] These probabilities are given in Figure 3 as a function of lateral separation and age of the deposit. Note that this simulation assumes that the ice layer began as a 10-cm thick sheet of pure ice and that thermal diffusion is negligible. At most ages, the probability is higher with increased lateral separation up to separations of 10 m. Greater separation does not improve the probability.

[16] Next we determine the probability of retaining a solid block of ice (Figure 4). The condition chosen for coherence is that there is a large abundance of ice ($f_{ice} > 0.5$) and that the difference between the abundance in the two columns is small compared to the average value ($|f_{ice}(A) - f_{ice}(B)| < 0.2 \langle f_{ice} \rangle$). Coherence on the size scale on order of the radar wavelength produces a strong radar circular polarization ratio (CPR) enhancement [e.g., *Spudis et al.*, 2010]. For Mini-RF and Mini-SAR, the relevant scale is ~ 10 cm. Integrated over the original depths containing ice, the lateral correlation decreases with age. The probability of 10-cm size ice blocks remaining as a function of age can be fit by the function $P_{block} = 0.904 - \log(t)/3.108$. Detectable ice blocks should remain for ~ 100 Myr. The ice blocks become too small by 100 Myr.

4. Discussion

[17] Owing to the spatial resolution of orbital neutron spectroscopy, large area averages from the model runs are the best representation of neutron data. Neutron spectroscopy,

which is sensitive to about 1 m depth, would therefore be detecting ice that has been deposited within the last 1000 Myr. These older deposits have a high degree of heterogeneity in both depth and lateral distribution. If several ice layers exist and one is on the surface, the standard dry-over-wet model used to convert neutron spectra into water abundances might underestimate the water abundance [*Lawrence et al.*, 2011]. Thus, quantifying the ice in a surface layer could improve models of neutron leakage used in converting neutron spectra to water abundances.

[18] Surface frost could appear two ways. First, it could be steadily deposited by volatiles migrating from other areas on the Moon. This case was studied by *Crider and Vondrak* [2003a] and is not addressed here. Secondly, volatiles on the surface can result from a partially buried ice layer, which may have resulted from episodic sources such as cometary impacts. As space weathering affects the surface more than it does the subsurface, surface abundances decrease rapidly without additional input. The model suggests that in the top 1 mm, values are heterogeneous soon after emplacement as ejecta slowly cover the layer and losses to space occur through photolysis and sputtering. The heterogeneous period is brief; and the surface frost becomes homogeneously low within a few 10 Myr after deposition. The presence of surface frost would likely imply the addition of volatiles at a steady rate. The concentration of surface frost could be used to constrain the rate of source/loss to the PSRs.

[19] Lateral coherence disappears quickly on the 20-cm scale according to these simulations. This implies that ice deposits in anomalous craters in the north polar region [*Spudis et al.*, 2010] would be young features—less than 100 Myr—if the features initially began as a 10 cm thick layer and if thermal diffusion is negligible. A thicker initial layer would take longer to break apart to the point of losing the high-CPR radar signature. However, thicker initial deposits require a large source. The model suggests that ice deposits in the larger cold traps including Cabeus, which

lack a high-CPR radar signature, are older than 100 Myr old or started as layers thinner than those detectable by radar.

[20] *Schultz et al.* [2010] concluded that the LCROSS impact excavated a 20–30 m diameter crater. Timing of the observations of water ice is consistent with the water being derived from a depth of 2–3 m. Furthermore, *Mitrofanov et al.* [2010] state that the impact region is enriched in water by a factor of ~ 2 compared to the surrounding area. This study defines “enriched” as both columns containing ice amounts greater than the average ice amount found from the set of runs. The likelihood of two columns separated by 10 m being enriched to that degree is negligible until the deposit is 1000 Myr old. Alternatively, the enrichment could occur with depth. Neutron spectroscopy is not sensitive to ice buried below 1-m of regolith. If the ice deposit in Cabeus is buried significantly below the depth to which neutrons are sensitive, this modeling would suggest that the ice deposit is older than 1000 Myr. These findings are more stringent than the constraint implied by the lack of radar CPR enhancement.

5. Conclusions

[21] Data on many spatial scales indicate that ice in lunar polar regions has a heterogeneous distribution. Space weathering, especially impact gardening, introduces heterogeneity even if an ice deposit is homogeneous initially. This process takes time, thus the degree of heterogeneity is related to the age of the deposit. Comparing models to data suggests that the ice deposits in lunar polar regions are generally old and generally buried. Possible exceptions do exist in the high CPR crater floors in the northern polar region, which are consistent with younger ages than deposits in the larger cold traps. Surface frost could indicate that there are some continually delivered volatiles.

[22] The next steps in lunar polar exploration are to characterize the deposits with in situ compositional and depth analysis. The heterogeneity due to space weathering guarantees that lateral variations will exist; and a static lander might have the misfortune of landing in a dry spot. These simulations suggest that a lateral range of ~ 10 m is optimal in the trade between minimizing the probability of probing a dry spot and minimizing mission duration. These simulations assumed that the ice layer began as a 10 cm-thick layer. Other initial conditions would produce different probabilities. Mass spectroscopy would identify constituents, which likely include multiple sources. With a small number of samples with depth, one could reliably determine what the peak concentration of the ice deposit was when it was emplaced, assuming thermal diffusion does not play a role. Although the age cannot be determined with one or two depth samples, increasing the number of depth distributions taken can increase the significance of the age inferred using the burial rate.

[23] The modeling described here has application to other airless bodies, including Mercury. Mercury’s cold traps are inherently different than the Moon’s in that radar observations are consistent with every permanently shadowed region containing relatively pure ice [*Slade et al.*, 1992]. They are interpreted to be young [*Crider and Killen*, 2005]. This study supports the conclusion that Mercury’s deposits are young, assuming that the volatiles have never been thermally mobilized. As MESSENGER acquires data, a

stronger comparison between the Moon and Mercury can be made.

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